Towards B_s Mixing With CDFII

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- Tevatron & CDFII
- B mixing measurement setup
- Br($B_s^0 \rightarrow D_s^- \pi^+$)
- Prospects

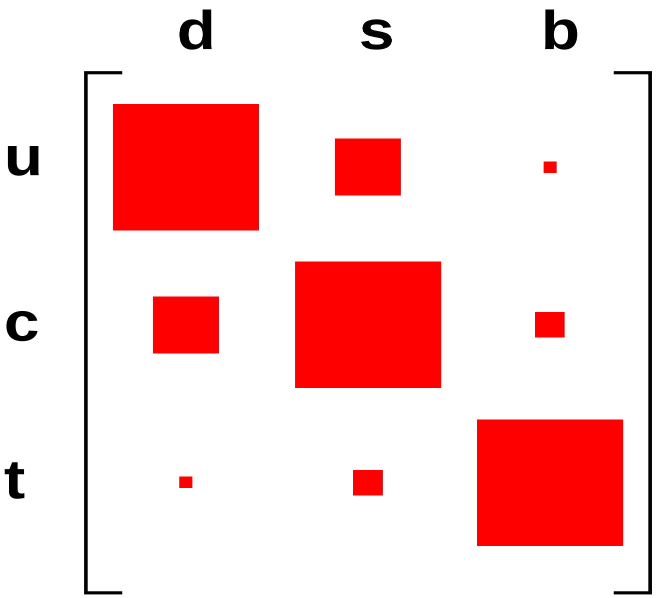
University of Pennsylvania HEP Seminar, Nov 11, 2003

Introduction/Roadmap

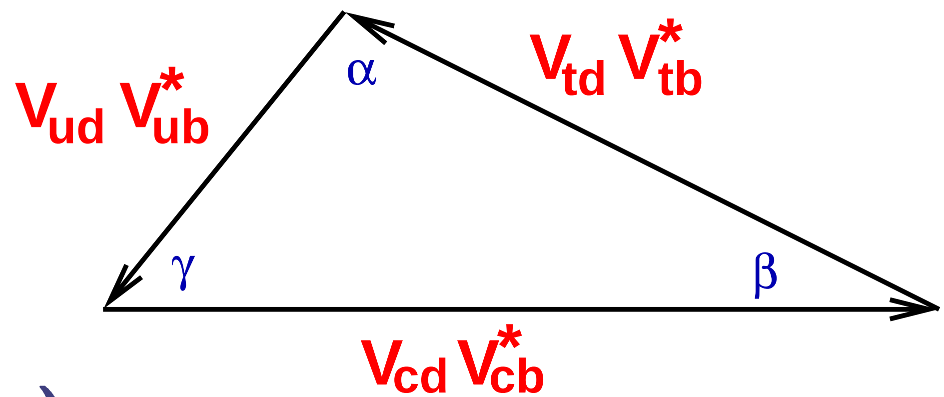
- measurements of B^0 and B_s mixing contribute to our understanding of weak interactions
- combined with measurements from B factories, they test the SM

- flagship measurement for CDF II B program
- overview measurement technique and issues
- focus on the measurement of $Br(B_s \to D_s^- \pi^+)$
- determines size and properties of our main sample
- use results of this analysis to project B_s mixing reach

Weak Interactions in the SM



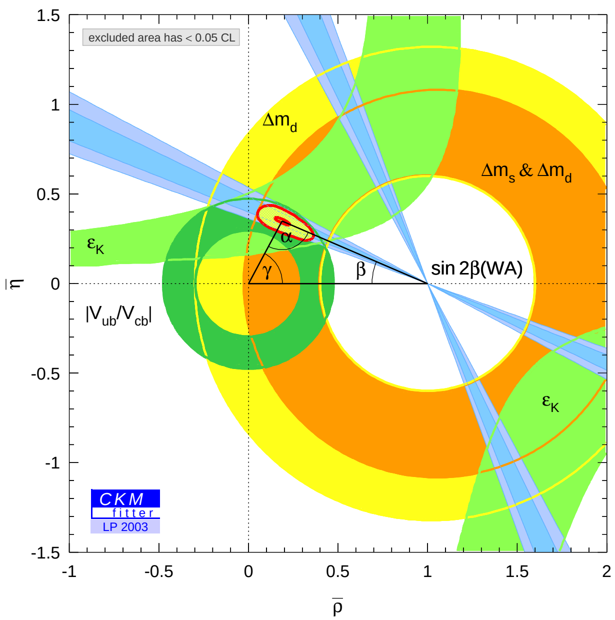
- CKM matrix: W$^{\pm}$ boson couplings to quarks
- area $\sim |V_{ij}|$
- interaction strength $\sim |V_{ij}|^2$
- unitary matrix: $VV^{\dagger} = 1$



- unitary triangle
- 1 observable phase ($\sim$ area, $\sim$ CP violation)

.. how does B_s mixing fit into this?

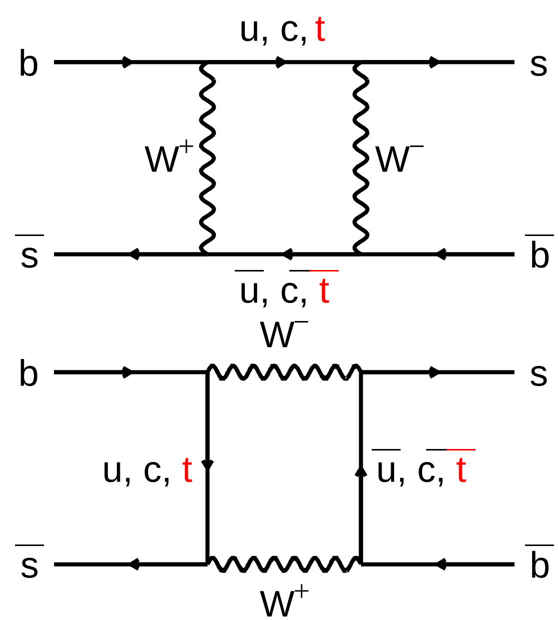
B Mixing and the Unitarity Triangle



Input for unitarity triangle fits:

- CP violation in kaon system
- $B \to \pi l \nu X$ vs $B \to D l \nu X$
- B_d, B_s meson mixing
- direct measurements of α, γ

- both B_d and B_s mesons mix
- ratio of mixing frequencies: **measures one side of the unitarity triangle ($|V_{td}/V_{ts}|$)**
- indir. meas: $\Delta m_s \leq\ 24\ \mathrm{ps}^{-1}$
- overconstrain $\to$ **test SM**

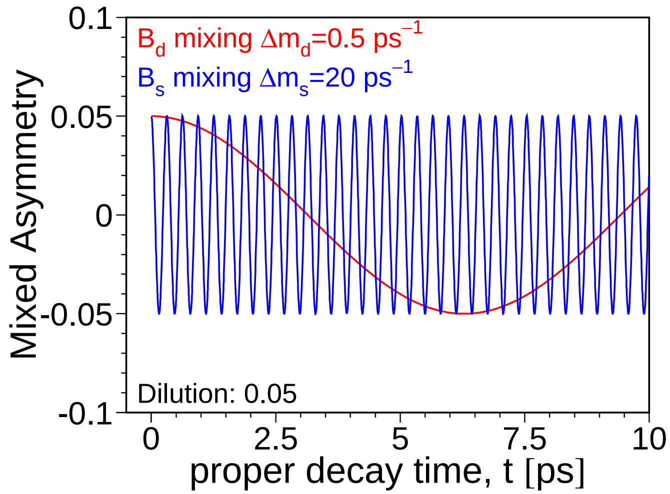


$B_{(s)}$ Mixing Measurement Ingredients

Per B meson decay,

- determine decay flavor [use flavor specific states]
- identify B meson production flavor [flavor tagging]
- measure B proper decay time [ct resolution]

Time-dependant asymmetry:



$$\begin{aligned} A_{mix}(t) &= \frac{N^{obs}_{unmix}(t) - N^{obs}_{mix}(t)}{N^{obs}_{unmix}(t) + N^{obs}_{mix}(t)} \\ &= (2p-1) \cdot \cos(\Delta m \cdot t) \end{aligned}$$

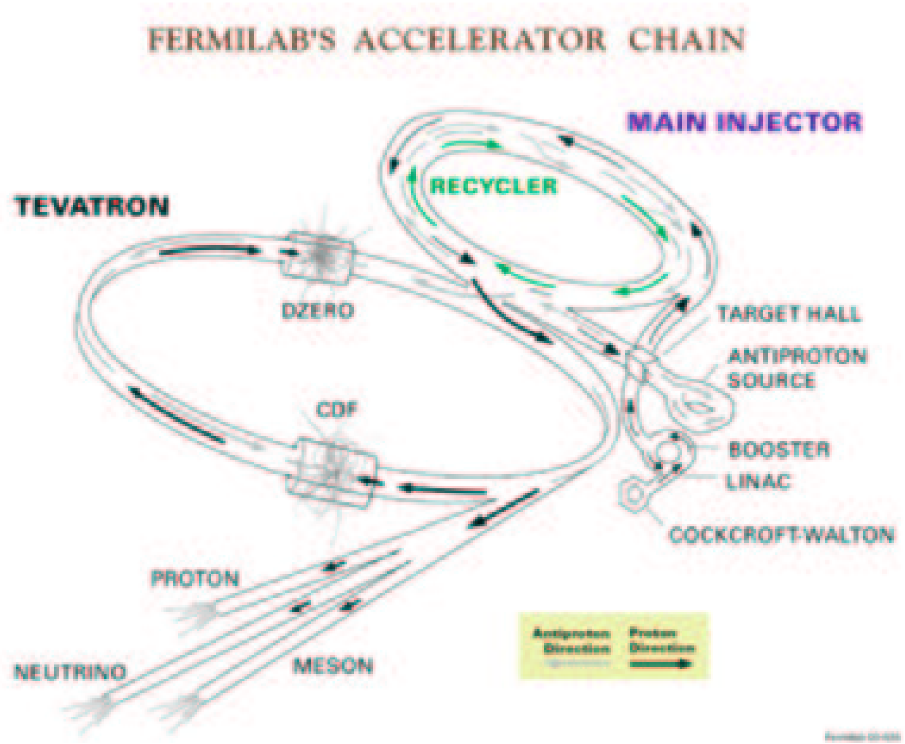
Oscillation amplitude: $2p - 1 = D$ [dilution]

$$\text{Significance} = \sqrt{\frac{\epsilon D^2}{2} e^{\frac{-(\Delta m)\sigma(c\tau)}{2}}} \frac{S}{\sqrt{S+B}}$$

Apparatus: Tevatron

Main Injector

- New injection stage for Tevatron
- Ability to accelerate and deliver higher intensity of protons
- More efficient $\overline{\mathrm{p}}$ transfer
- $\overline{\mathrm{p}}$ recycler (in progress)

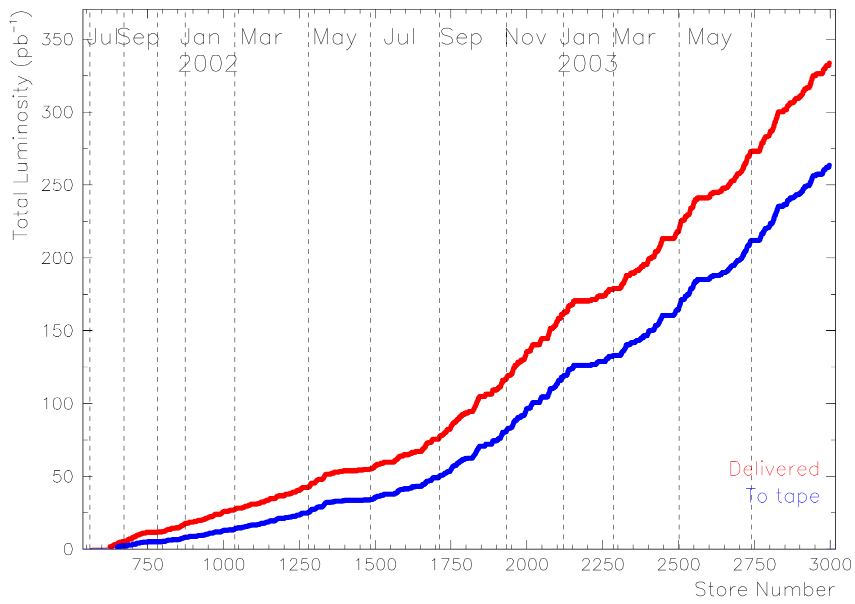


- Higher Collision rate: 396ns (36x36 bunches)
  $\Rightarrow$ 5-10 Higher Luminosity than Run I
- Higher C.M. Energy:
  Run I: 1.8 TeV $\rightarrow$ Run II 1.96 TeV

Tevatron Luminosity

Tevatron Performance

- **Below expectation but improving**
  - Record luminosity: $4.8 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Now consistently $4 - 7\ \mathrm{pb}^{-1}$per week



At CDF:

- $330\ \mathrm{pb}^{-1}$ delivered, $260\ \mathrm{pb}^{-1}$ recorded
- $\sim 200\ \mathrm{pb}^{-1}$ all important systems on
- analyses shown use $12 - 120\mathrm{pb}^{-1}$ (depending on when they were done)

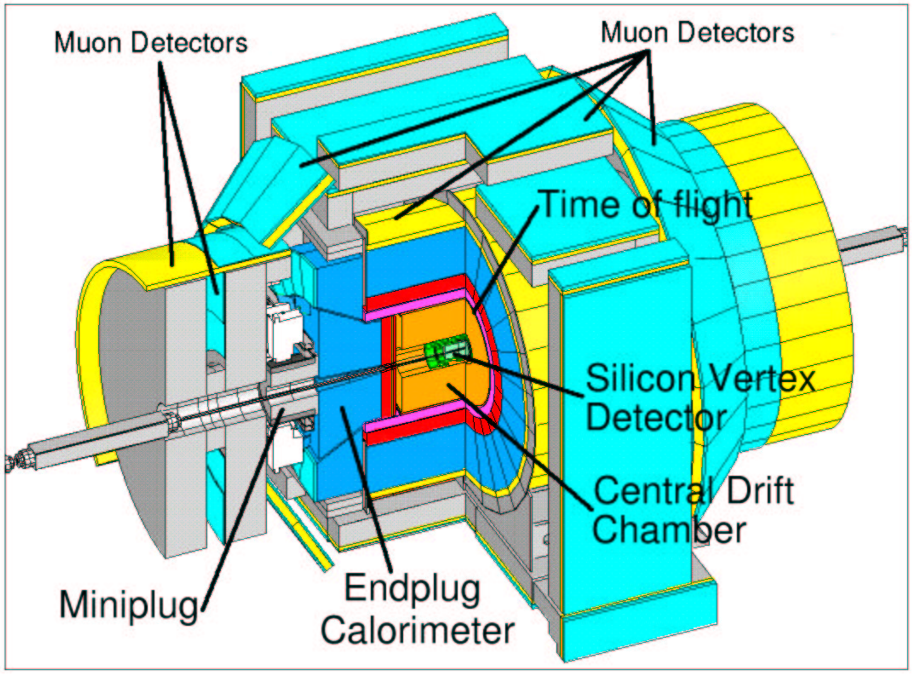
Apparatus: The CDF II Detector

Inherited from Run I:

- Central Calor. ($|\eta| < 1$)
- Solenoid (1.4 T)

Partially new:

- Muon System (extended to $|\eta| < 2$)



Completely new:

- 3D Silicon Tracker ($|\eta| < 2$)
- Faster Drift Chamber
- Plug and Forward Calorimeters, Time Of Flight
- Trigger System (trigger on displaced vertices)

B Mixing in $p\bar{p}$ collisions

- produce all B species: B^0, B^+, B_s, B_c, Λ_b
- huge B production cross section: $\sim 100\ \mu\mathrm{b}$
  ($3 - 5\ \mu\mathrm{b}$ "reconstructable")
  at $4 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, 150 Hz reconstructable B's
- large inelastic ($\sigma \times 1000$) background
  $\Rightarrow$ triggering very important
- B's boosted in the transverse plane (ct measurement)
- less production flavor information than at e^+e^-
- B^0 mixing routinely done in Run I

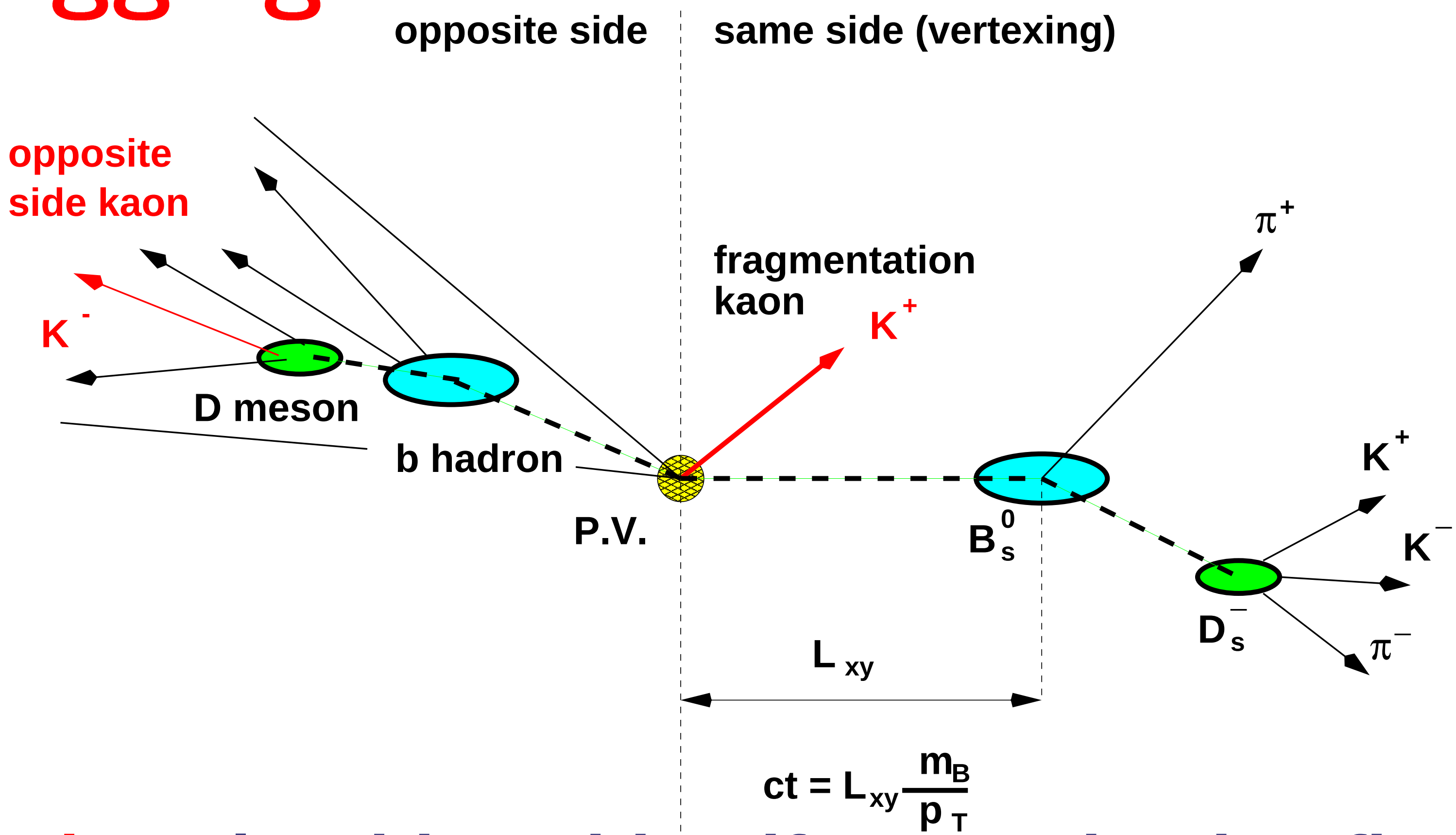
Reminder: Measurement Ingredients

Per B meson decay,

- **determine decay flavor [use flavor specific states]**
- **identify B meson production flavor [flavor tagging]**
- **measure B proper decay time [ct resolution]**

Focus: flavor tagging techniques

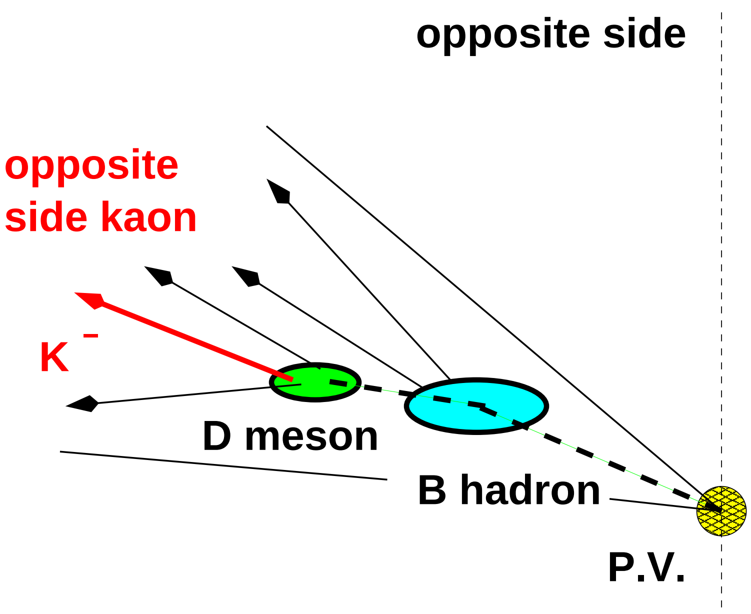
Tagging The Production Flavor



- **Tagging** algorithms identify B production flavor
- **Opposite Side Tagging**: B's produced in pairs, identify the flavor of the opposite B meson
- **Same Side Tagging**: hadronization π/K charge is correlated to B_d/B_s production flavor

Tagging: Opposite Side Tagging

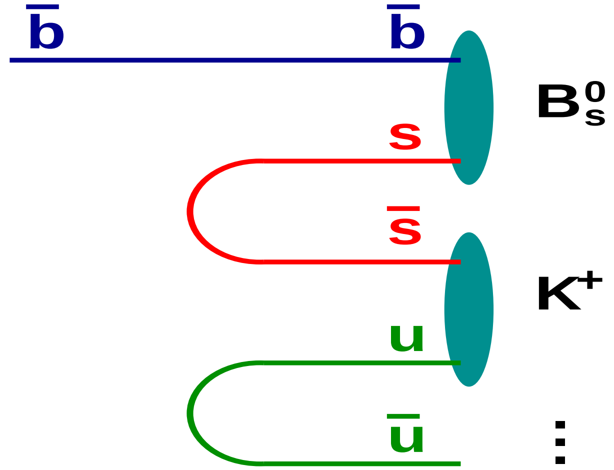
- **Lepton Tagging**: find lepton from $B \to Dl\nu X$
- **Jet Charge Tagging**: momentum-weighted sum of track charge in B jet (+ displacement)
- **Kaon Tagging**: assume $b \to c \to s$ decay, find kaon in B jet

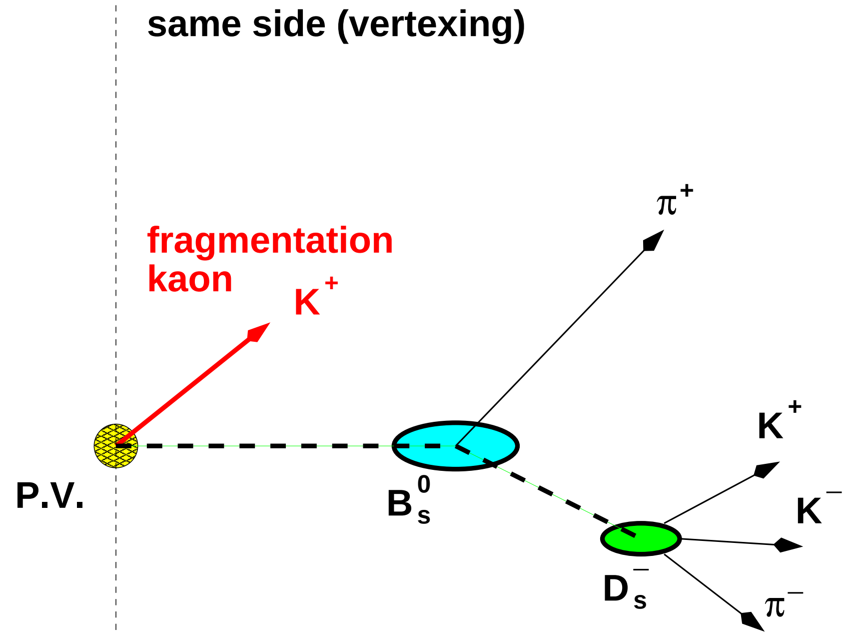


- Difficulties with OST:
- 20-40% opposite side B's outside detector acceptance
- B^0, B^0_s mix $\to$ production flavor information lost

Tagging: Same Side Tagging

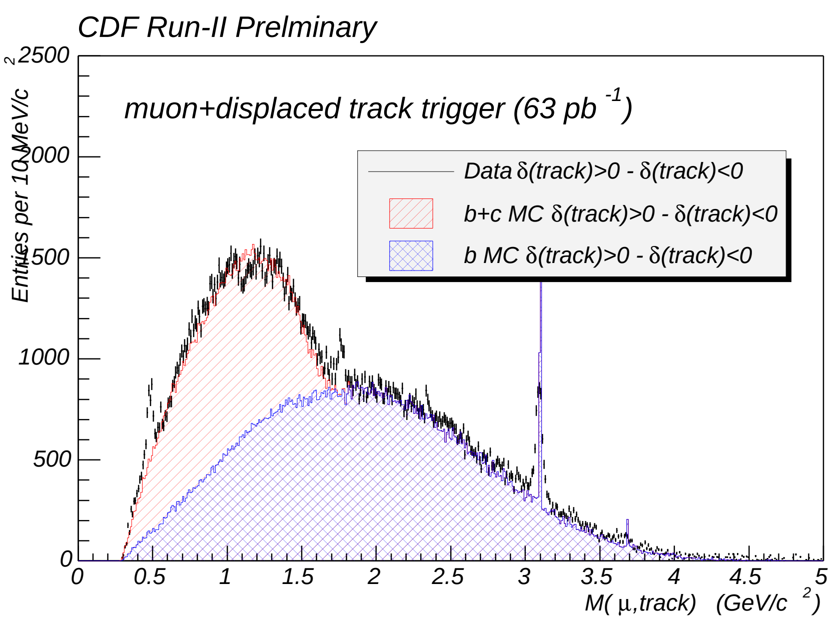
Exploit signature of B_s hadronization:

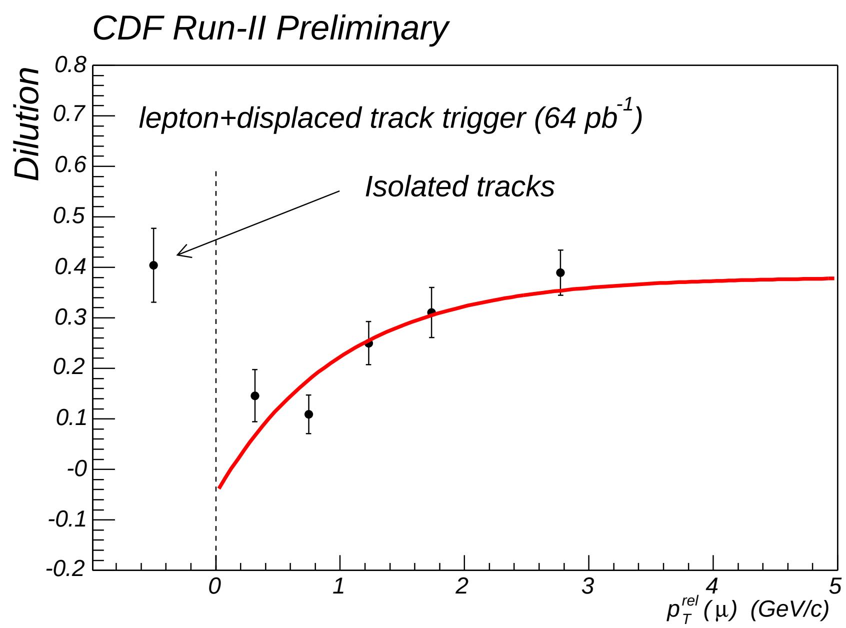




- 80% of tracks in event are pions [kaons $\sim 10\%$]
- fragmentation tracks are soft $\longrightarrow$ TOF particle ID
- Run I B^0 mixing using pion SST
- expect improvement using TOF particle ID
- combined (OST + SST) tagging power: $\epsilon D^2 \sim 5\%$

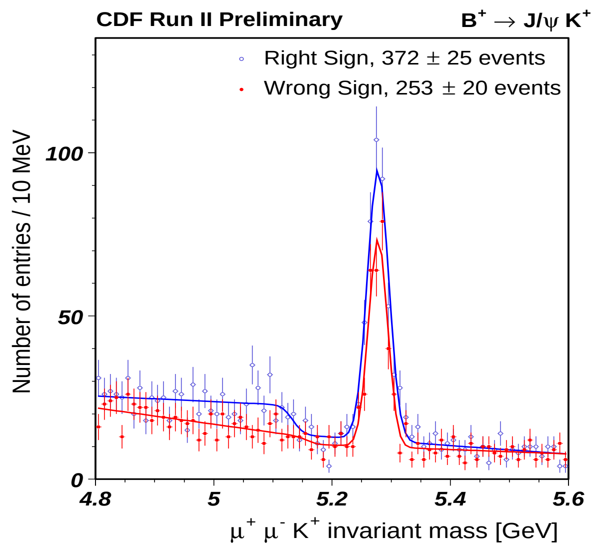
Tagging Efforts in Run II

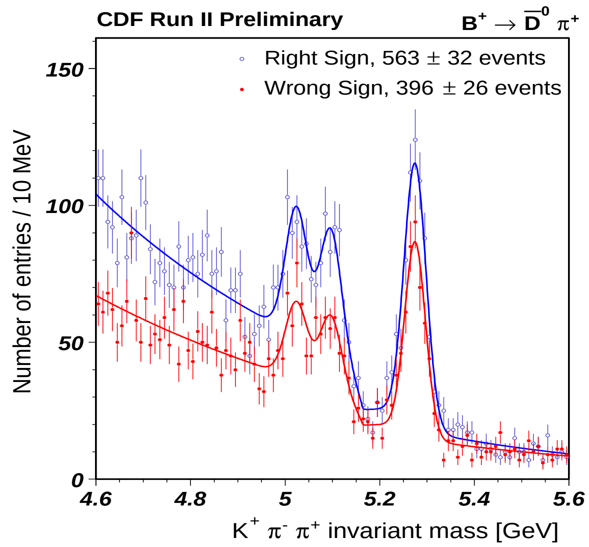


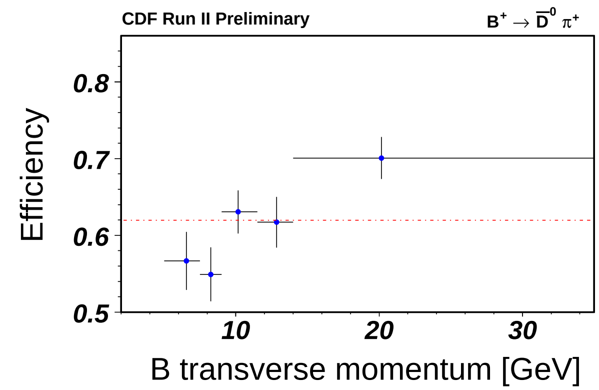


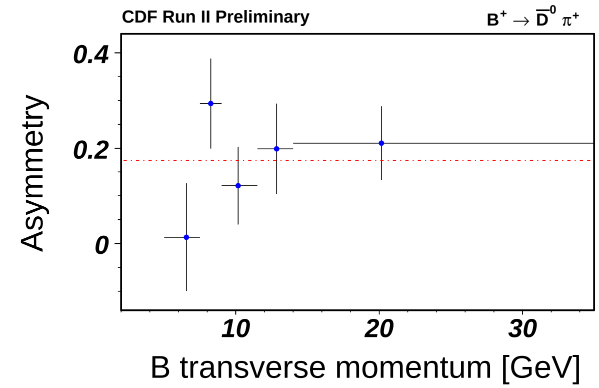
- **trigger on lepton + displaced track (SVT)**
- **signal: l-track intersection $ct > 0$**
- **background: l-track intersection $ct < 0$**
- **require $2\,\mathrm{GeV}/c < \mathrm{m}(l, \mathrm{track}) < 4\,\mathrm{GeV}/c$**
- **$\sim$ 500k inclusive B decays $\rightarrow$ test taggers**
- **example: measure dilution of soft muon tag**

Tagging Efforts in Run II (cont)









- **fully reconstructed B^+ decays**
- **measure efficiency and dilution**
- **example: same side pion tag**
- $B^+ \to J/\psi K^+$: $\epsilon D^2 = 2.4 \pm 1.2(stat)\%$
- $B^+ \to \overline{D^0}\pi$: $\epsilon D^2 = 1.9 \pm 0.9(stat)\%$
- **Run I** $J/\psi K^*$: $\epsilon D^2 = 1.8 \pm 0.4(stat)\%$

Reminder: Measurement Ingredients

Per B meson decay,

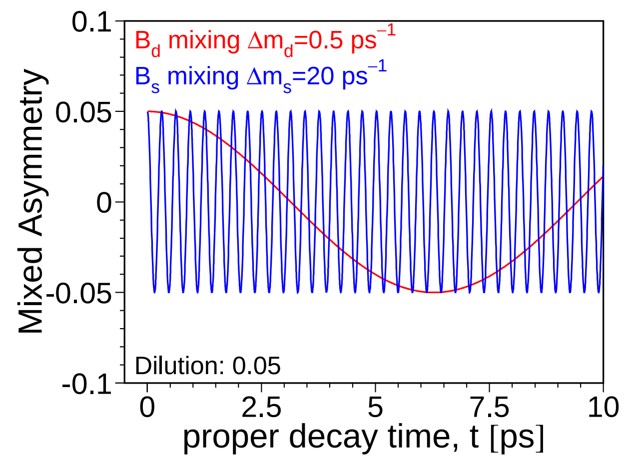
- determine decay flavor [use flavor specific states]
- identify B meson production flavor [flavor tagging]
- measure B proper decay time [ct resolution]

Focus: ct Resolution

- importance of ct resolution
- triggering on fully hadronic B (and charm) decays
- digression: D meson mass difference measurement
- rate of fully hadronic B_s decays
- $\Rightarrow$ mixing reach projection

Precise ct Measurements

- **rapid oscillations:**
  $\Delta m_s \geq 13.1\ \mathrm{ps}^{-1}$ **(90%CL, PDG)**
  (indir. meas: $\leq 24\ \mathrm{ps}^{-1}$)
- **very good ct resolution needed:**

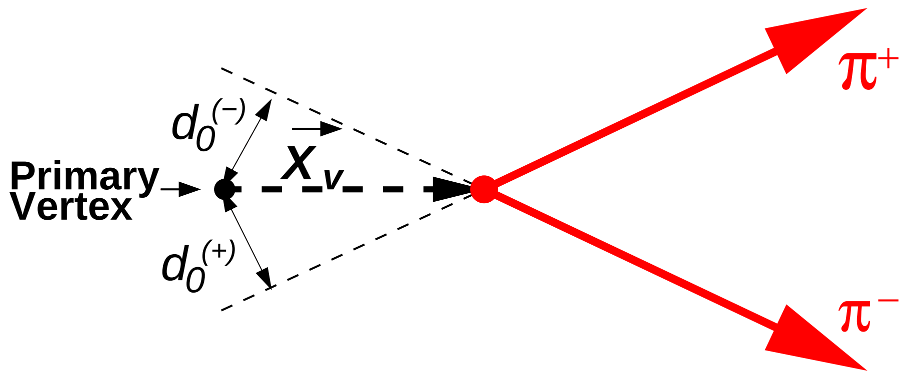


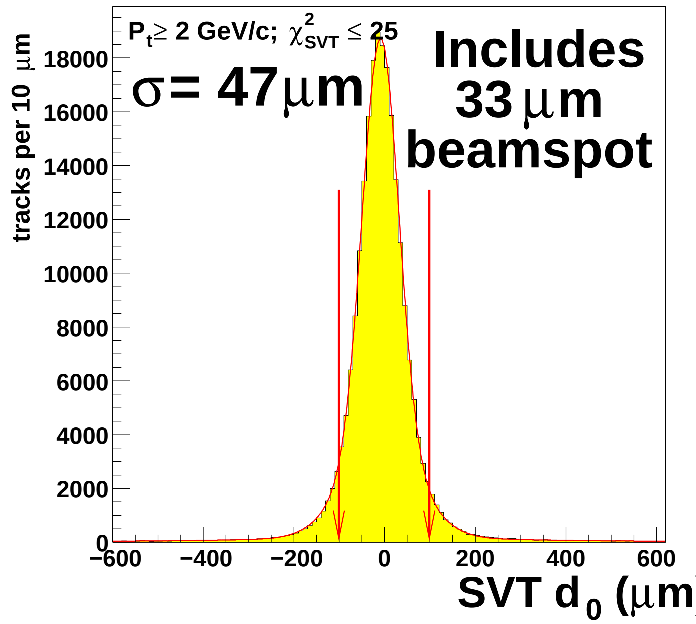
$$\sigma_{ct} = \left(\frac{\sigma_L}{\gamma\beta}\right) \oplus \left(\frac{\sigma_{\gamma\beta}}{\gamma\beta}\right) \cdot ct$$

- **semileptonic decays: B momentum error $\sim 15\%$**
- **hadronic decay ($B_s \to D_s\pi$) negligible ($\sim 0.5\%$)**
- **using base RunII silicon : 60 fs $\Delta m_s \sim 17\ \mathrm{ps}^{-1}$**
- **layer of Si on beampipe: 45 fs $\Delta m_s \sim 22\ \mathrm{ps}^{-1}$**
- **Problem: how do we trigger on these decays?**

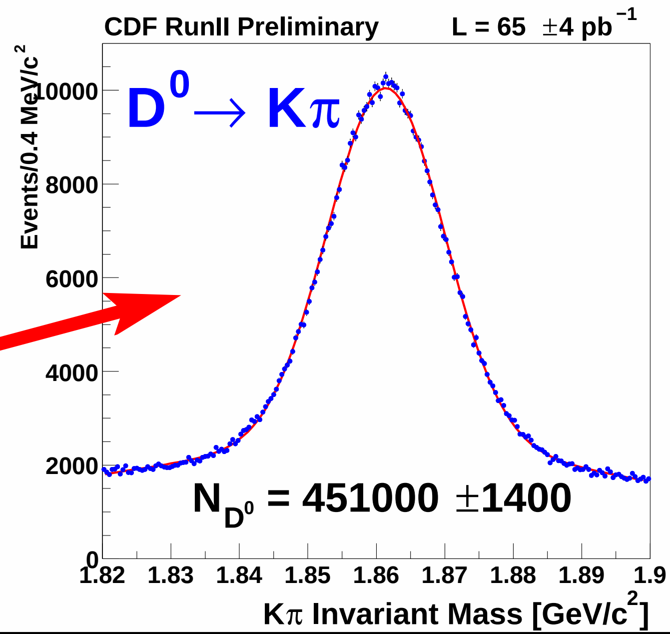
Triggering on displaced tracks

- trigger $B \to \pi\pi, B_s \to D_s\pi$
- challenge: read out SVX and track at 10's of kHz $\to$ SVT

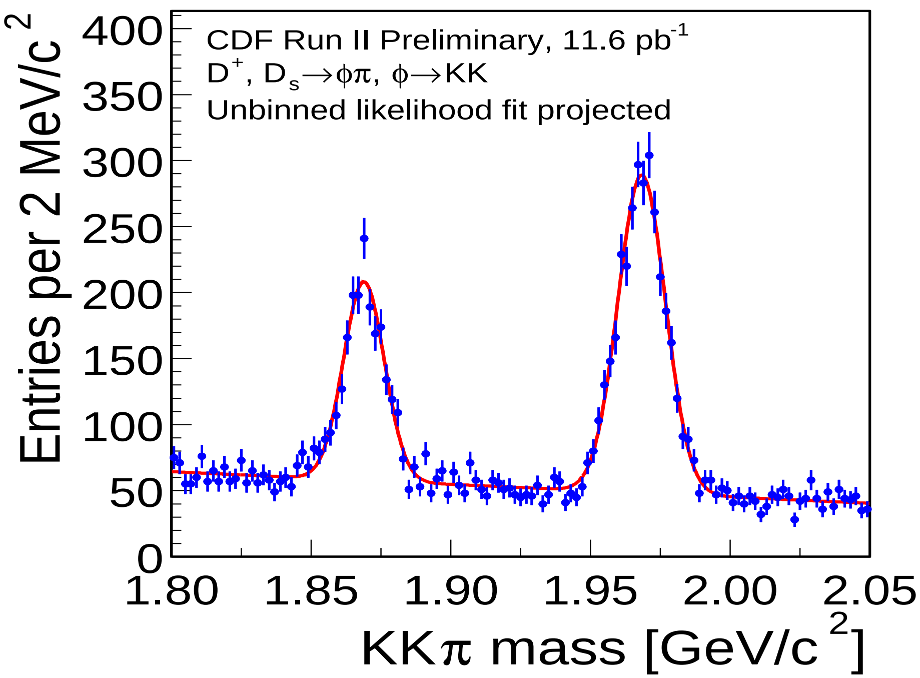


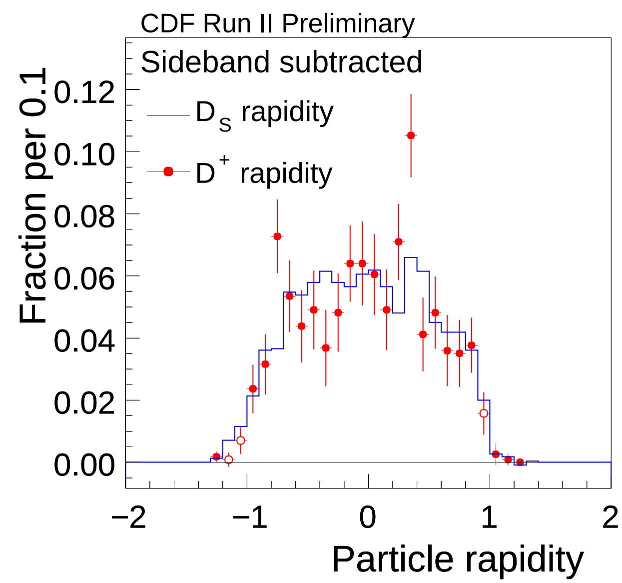


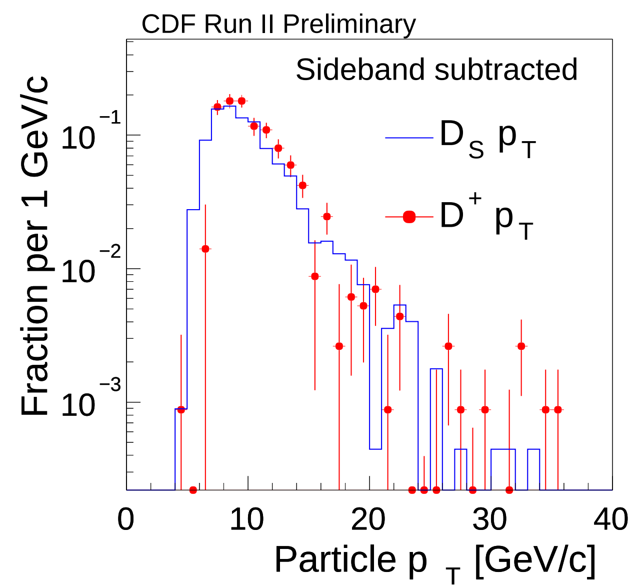
- trigger on 2 displaced tracks
  ($p_T > 2$ GeV/c, 120 μm $< |d_0| <$ 1 mm)
- huge charm samples gathered
- with small int. luminosity, competitive charm analyses



D Meson Mass Difference



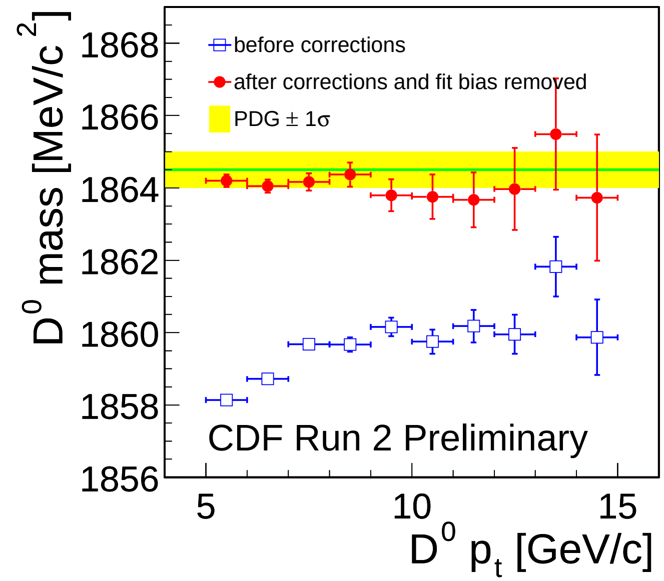


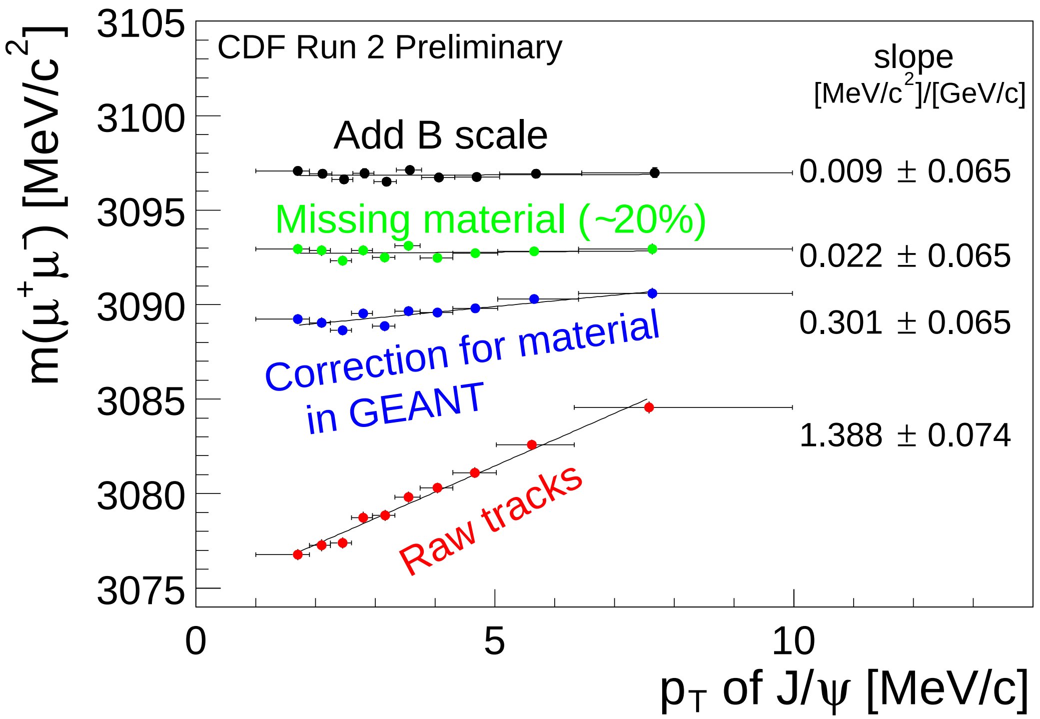


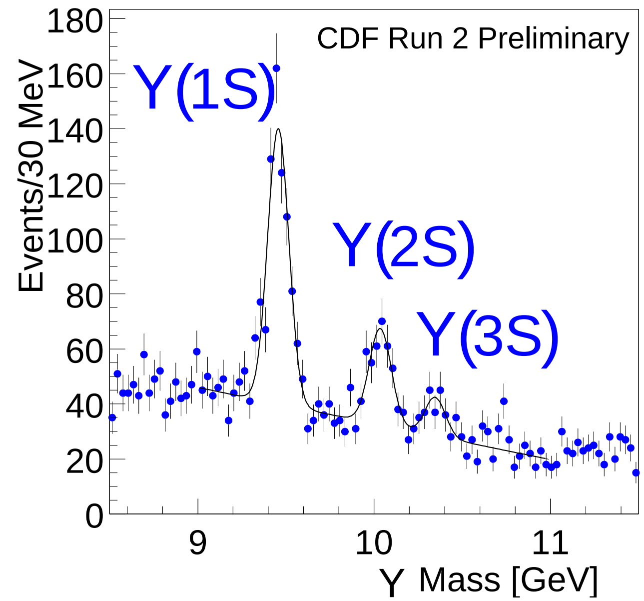
- **$1.4\mathrm{k}\ D^+, 2.4\mathrm{k}\ D_S^+ \to \phi\pi^+$**
- **mass resolution $\sim 8\,\mathrm{MeV}/c^2$**
- **similar kinematics**
- **expect small syst. errors**

Momentum Scale Calibration

- study J/ψ's to calibrate:
  - energy loss in detector
  - magnetic field value
- crosscheck with other decays







Mass Difference Result

$m(D_s^+) - m(D^+) = 99.41 \pm 0.38(stat) \pm 0.21(syst)\ \mathrm{MeV}/c^2$

PRD 68 (2003) 072004 - First Tevatron Run II publication

systematics small, dominated by bkg model:

Effect	Syst. $[\mathrm{MeV}/c^2]$
fitting	0.14
event selection	0.11
momentum scale	0.10
tracker effects	0.06
calibration procedure	0.03
Total	0.21

- **PDG '02:** $99.2 \pm 0.5\ \mathrm{MeV}/c^2$
- **CLEO2 (1998):** $99.5 \pm 0.6 \pm 0.3\ \mathrm{MeV}/c^2$
- **BaBar (2002):** $98.4 \pm 0.1 \pm 0.3\ \mathrm{MeV}/c^2$

Reminder: Measurement Ingredients

Per B meson decay,

- **determine decay flavor [use flavor specific states]**
- **identify B meson production flavor [flavor tagging]**
- **measure B proper decay time [ct resolution]**

Focus: Rate of fully reconstructed hadronic B_s decays

- **use as input for mixing reach projection**

Fully Hadronic B_s decays

- good for B_s mixing because of good ct resolution
- $B_s^0 \to D_s^- \pi^+$ "golden mode"
  - fully hadronic, flavor specific
  - few tracks $\to$ "easy" to trigger, reconstruct
  - $D_s^- \to \phi^0 \pi^-$, $\phi^0 \to KK$ narrow resonance (cut on KK invariant mass $\to$ good S/N)
- first observed at LEP
- branching fraction? (PDG: <13%, 95% CL) (determines number of B_s available for mixing)
- initially assumed $\sim Br(B^0 \to D^- \pi^+)$
- background composition? S/B?
- answers: branching fraction measurement

Rate of B_s vs B^0

- want to understand rate of $B_s \to D_s^- \pi^+$
- compare to similar decay $B^0 \to D^- \pi^+$
- count how many B_s vs B^0 are reconstructed
- what is different?

- rate of B_s production different from B^0
- f_s/f_d probability for b to hadronize as B_s/B^0

- final state $D_s \to \phi\pi$ vs $D^- \to K^+\pi^-\pi^-$
- account for by using PDG ratio of BR's

- kinematics slightly different $\to$ efficiency?
- $\epsilon = \epsilon(acc) \cdot \epsilon(det) \cdot \epsilon(trig) \cdot \epsilon(rec)$
- will need to consult Monte Carlo simulation for this

$Br(B_s^0 \to D_s^- \pi^+)$ Measurement:

We measure the ratio of branching fractions:

$$\frac{f_s}{f_d} \cdot \frac{Br(B_s^0 \to D_s \pi)}{Br(B^0 \to D^- \pi)} = \frac{N(B_s^0)}{N(B^0)} \cdot \frac{\epsilon(B^0)}{\epsilon(B_s^0)} \cdot \frac{Br(D^+ \to K\pi\pi)}{Br(D_s \to \phi\pi, ..)}$$

- **control sample:** $B^+ \to \overline{D^0}\pi^+$ **and corresponding BR relative to** $B^0 \to D^- \pi^+$
- **N(**B_s^0**), N(**B^+**), N(**B^0**) obtained from fits to data**
- $\epsilon(B^0)$ **/** $\epsilon(B_s^0)$**,** $\epsilon(B^0)/\epsilon(B^+)$ **from realistic MC**
- $BR(D^-/D_s^-/D^0)$ **are taken from PDG**

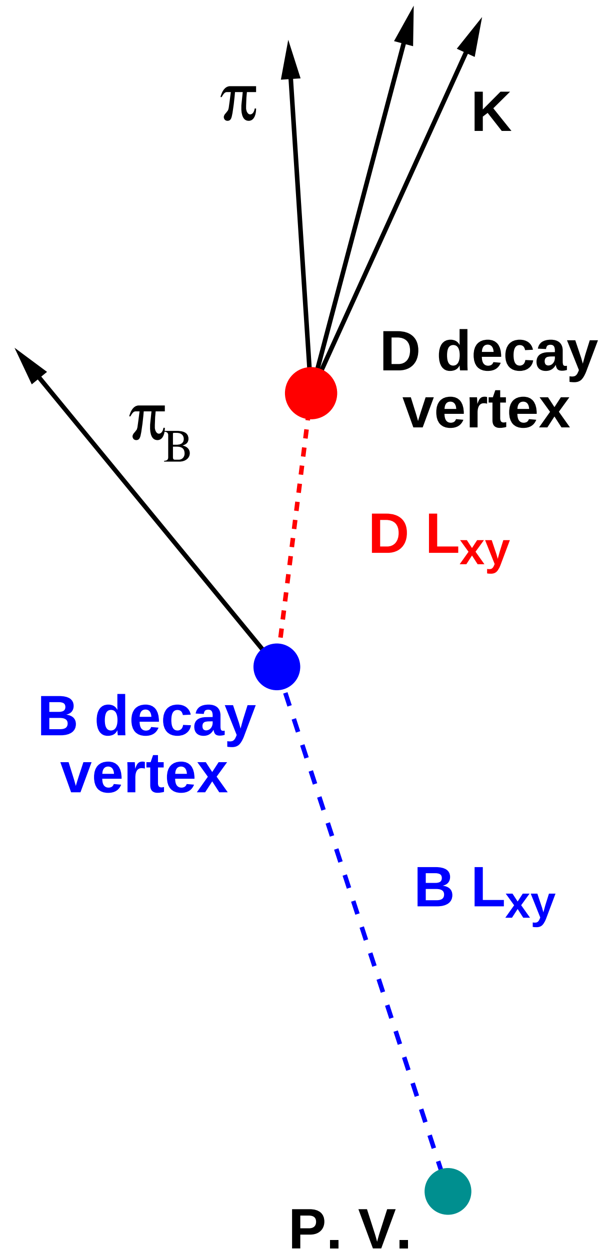
Key issues:

- **reconstruction of** B **mesons with good** S/B
- **robust and correct extraction of** $N(B)$
- **realistic trigger and analysis simulation**

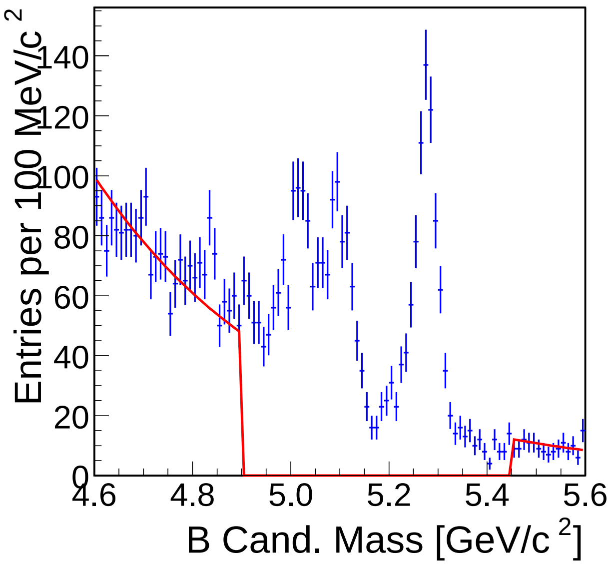
Typical B meson selection cuts:

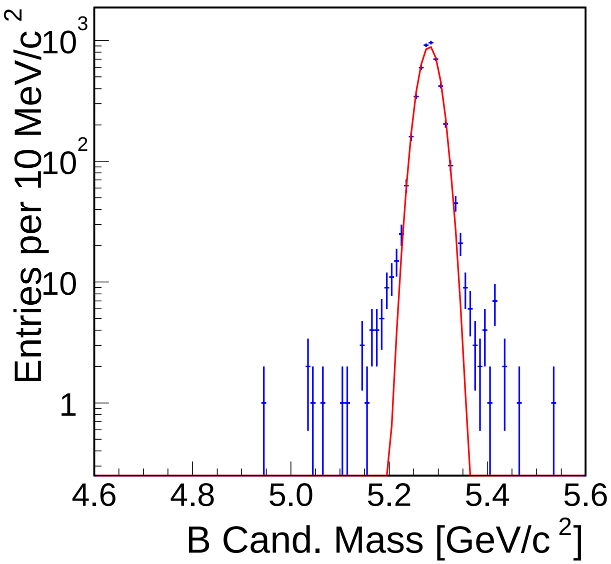
- $\chi^2_{r,\varphi}(D) < 14$
- $\chi^2_{r,\varphi}(B) < 15$
- $p_T(D) > 3.5$ GeV$/c$
- $p_T(B) > 5.5$ GeV$/c$
- $L_{xy}(B) > 400\mu$m
- $L_{xy}(B \to D) > -150\mu$m
- $\Delta R(D, \pi_B) < 1.5$
- $p_T(\pi_B) > 1.6$ GeV$/c$
- $|d_0(B)| < 80\mu$m
- ϕ^0 mass cut for B^0_s

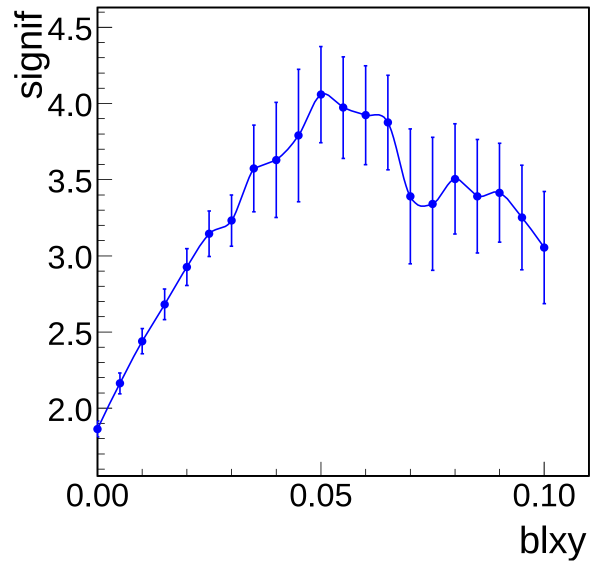
  (1010 MeV$/c^2 < m(\phi^0) < 1028$ MeV$/c^2$)



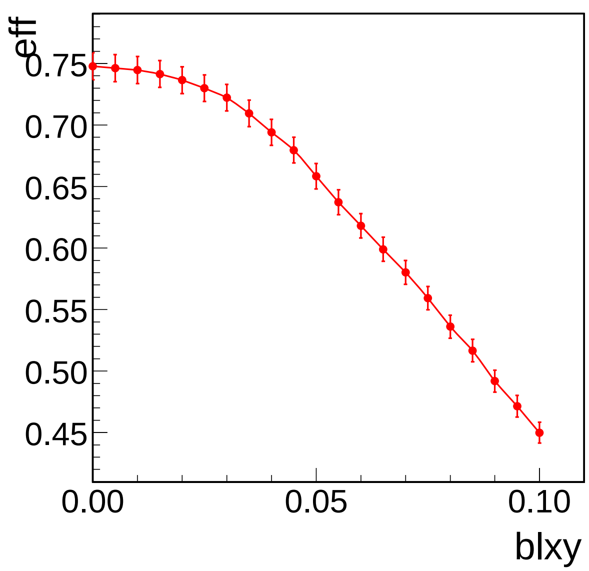
B Meson Selection Optimization:





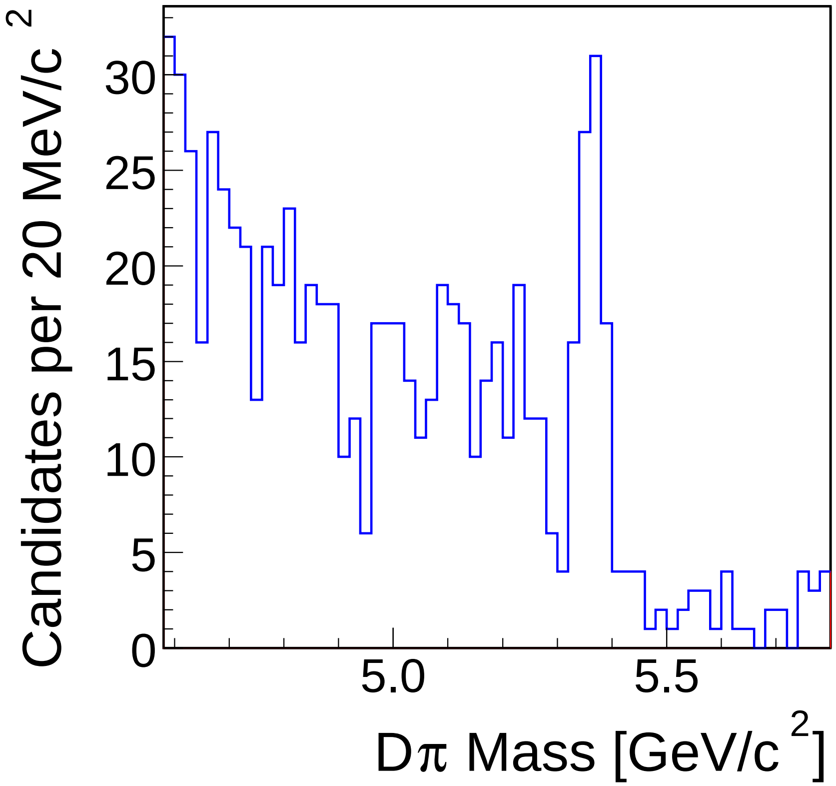


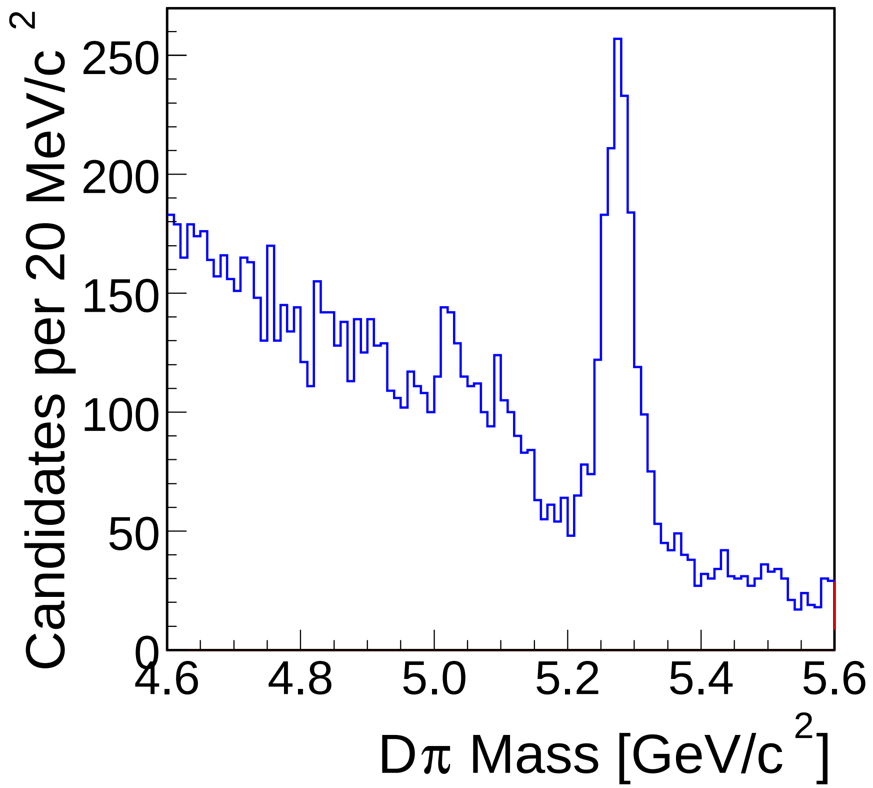
- optimize $S/\sqrt{S+B}$
- keep efficiency high
- background estimate from data
- signal estimate from scaled MC
- similar cuts from both studies



B Meson Mass Spectra:

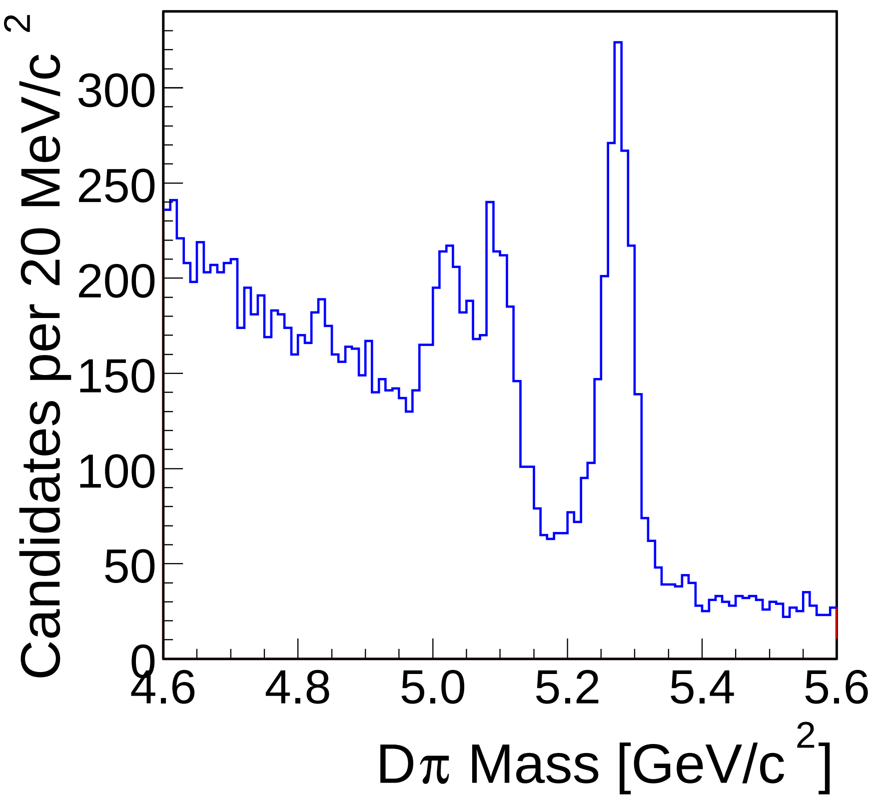
$B_s^0 \to D_s^- \pi^+$ $\qquad$ $B^0 \to D^- \pi^+$

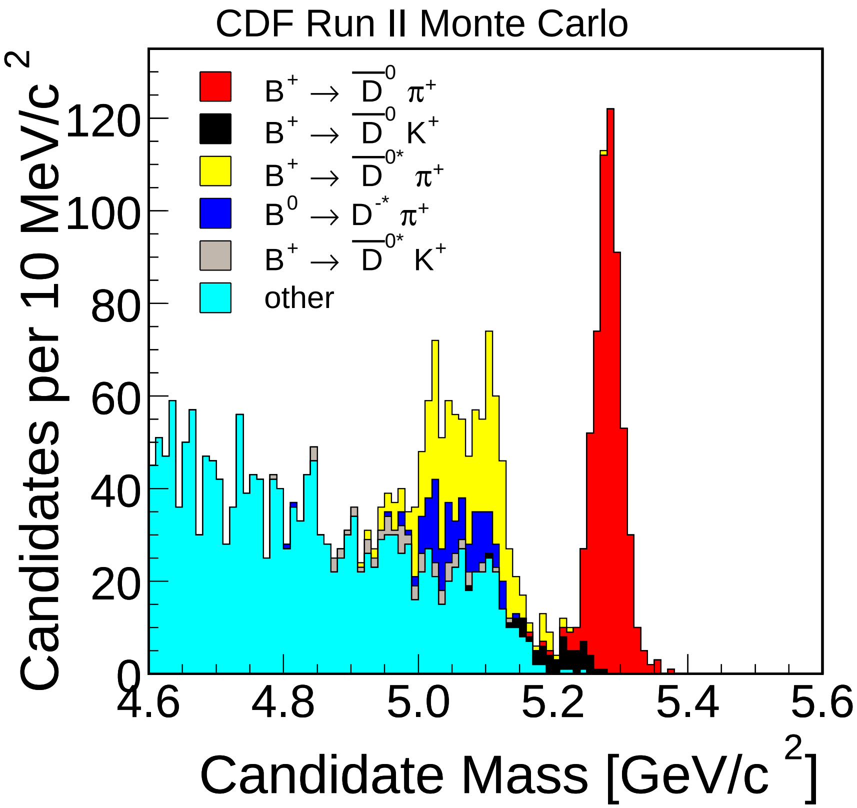




- B **mass peaks are quite clean** $(S/N > 2:1)$
- **spectra have interesting structures**
- **use Monte Carlo to study background shapes**

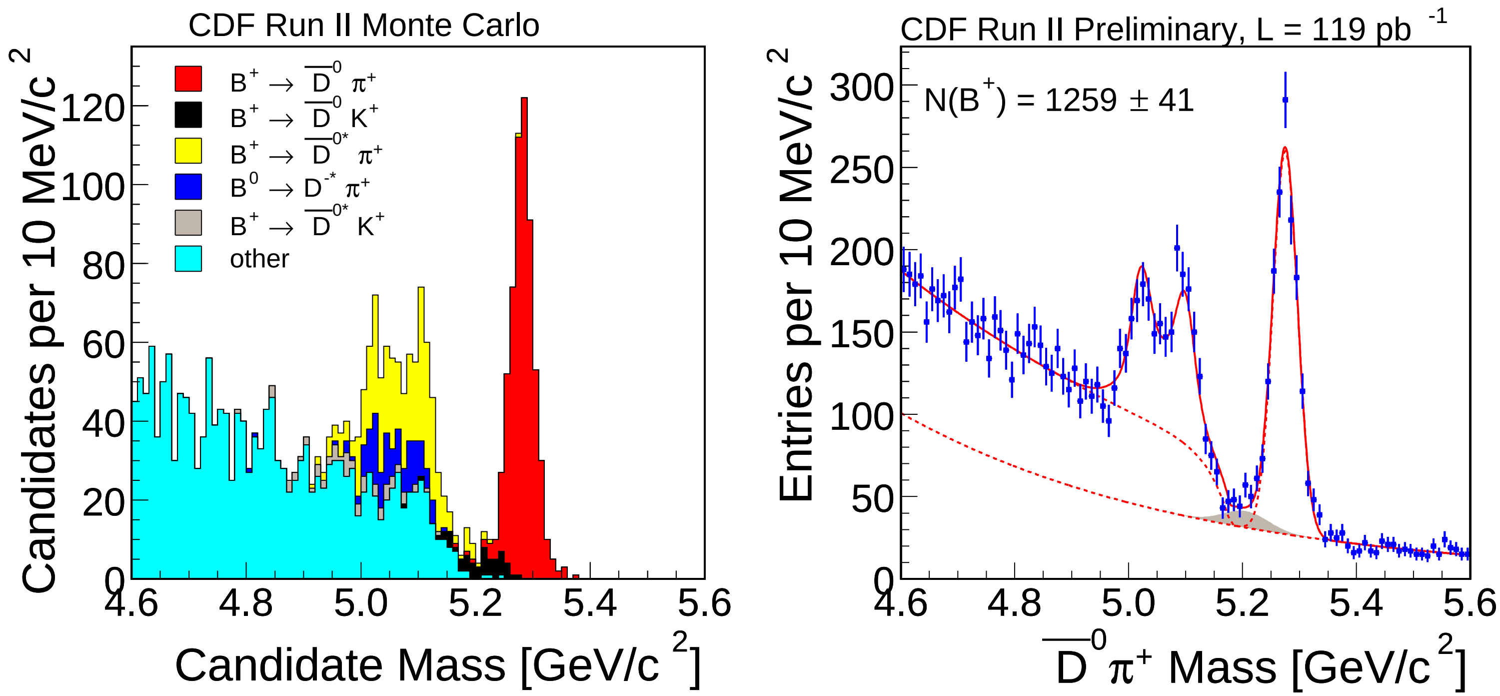
Background Shapes ($B^+ \to \overline{D^0}\pi^+$)





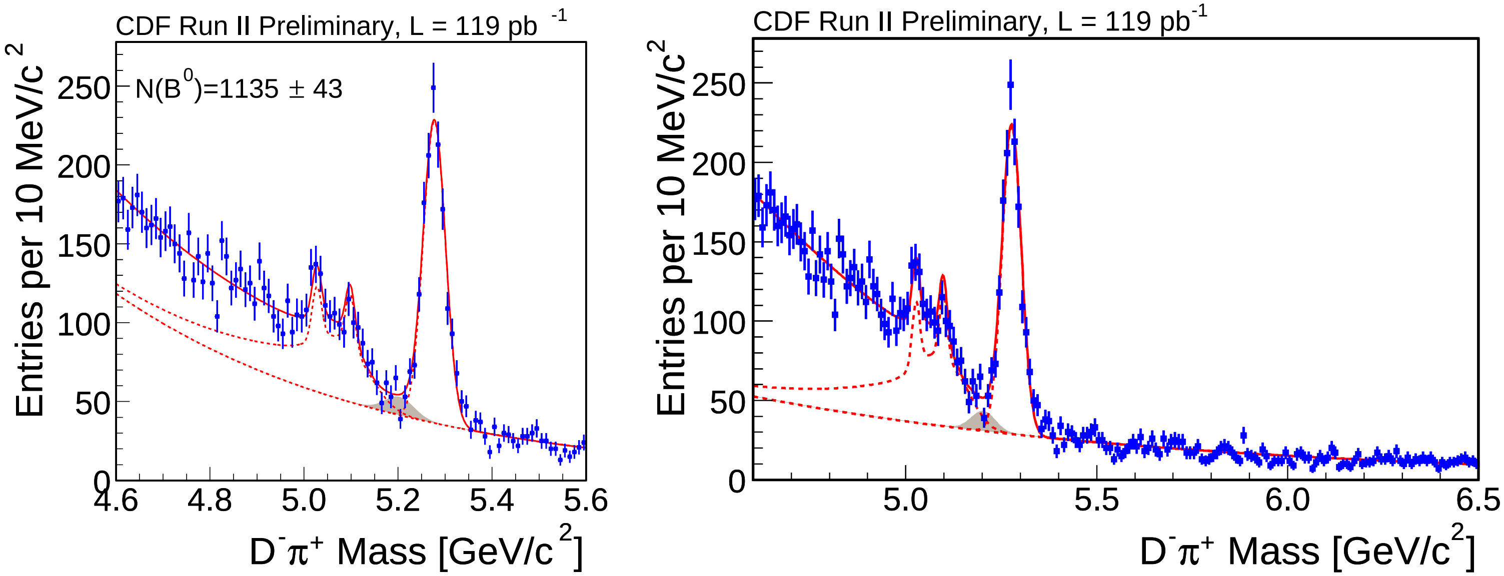
- **Monte Carlo:** $B \to \overline{D^0}X, \overline{D^0} \to K^+\pi^-$
- **GEANT simulation of detector response**
- **realistic trigger simulation**
- **spiky structures are signatures of D^* polarization**

Fitting With Templates:



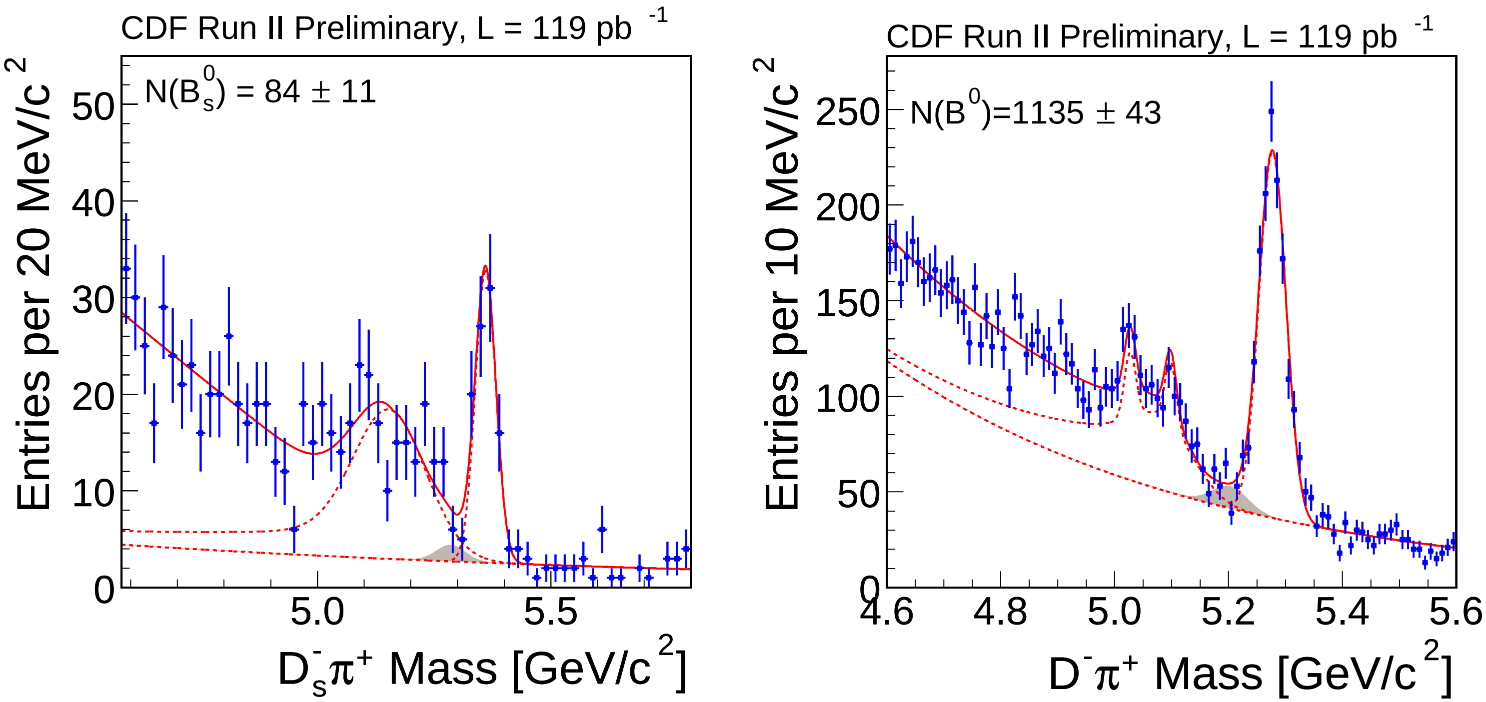
- decompose background into groups with similar features (spiky, Cabbibo suppressed, ..)
- based on Monte Carlo, create analytical templates
- extract shape parameters from MC
- keep shape parameters fixed in fit to data
- combinatorial background $\longrightarrow$ single exponential

Fit Result N(B) Stability



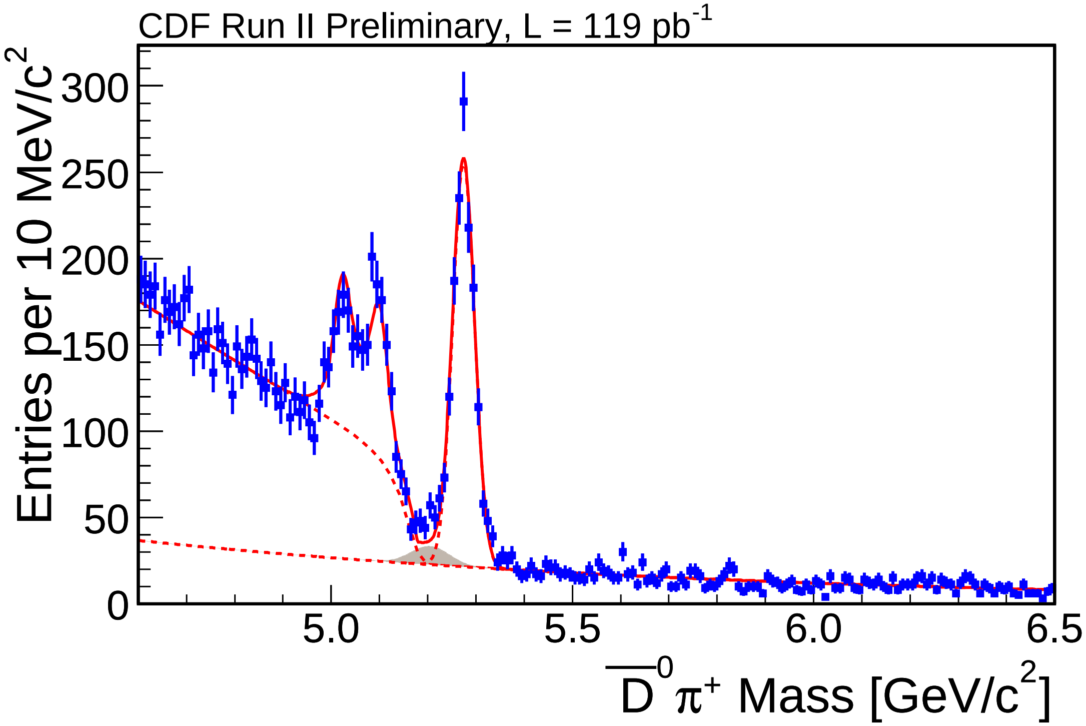
- how reliable is our counting method? (assign counting systematic error)
- vary shape parameters for templated background
- extend fit range, fix continuum parametrization
- fits result change up to $\sim 7\%$
- can improve background parametrization

Fit Results for B_s^0 and B^0



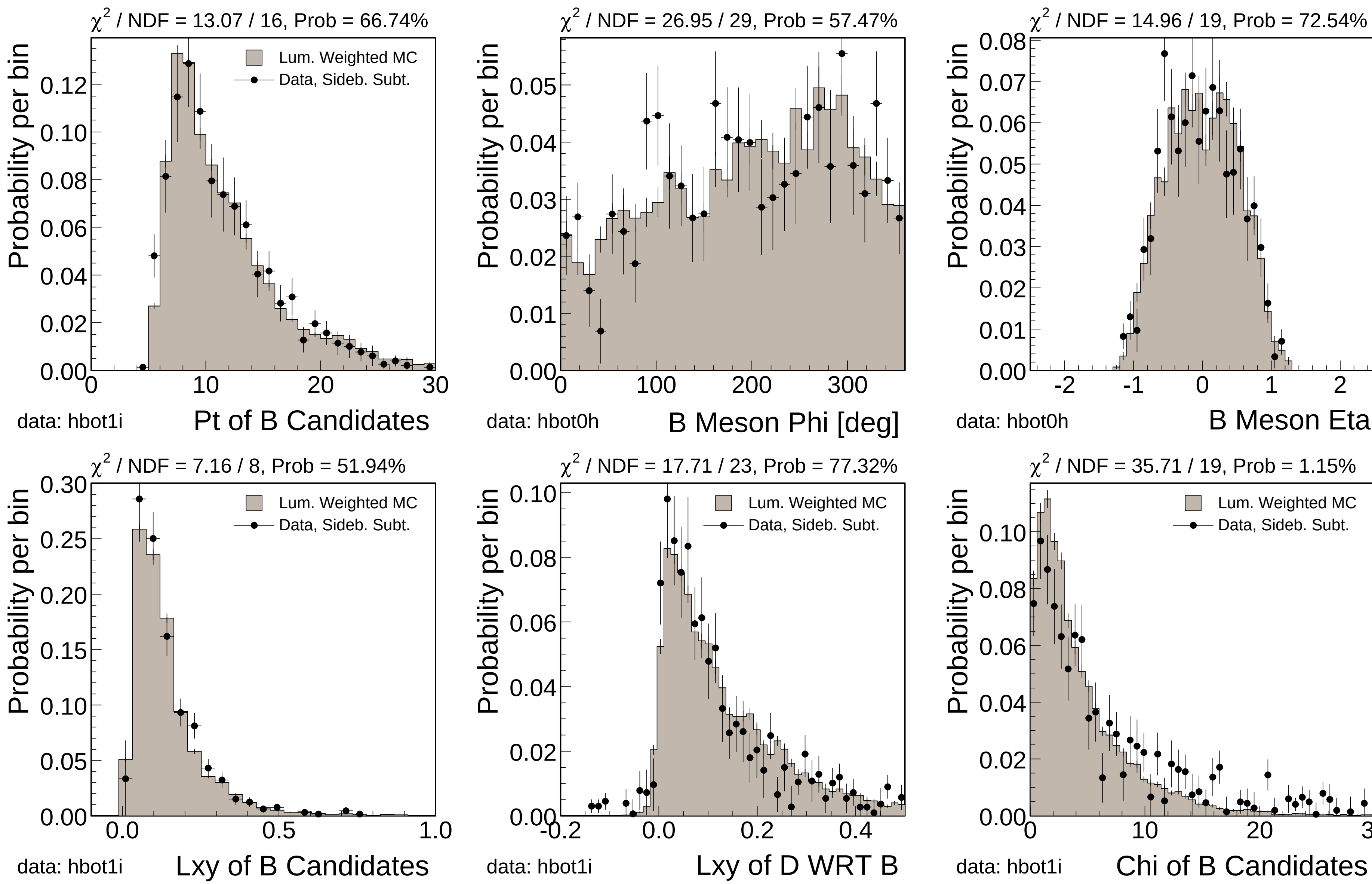
- **counting systematic error $\sim 7\%$**
- $84 \pm 11(stat) \pm 4(syst)$ B_s **candidates**
- $1135 \pm 43(stat) \pm 80(syst)$ B^0 **candidates**
- **this determines the ratio** $N(B_s)/N(B_d)$
- **remaining work: correct for detector effects (different efficiencies for B_s, B^0) $\Rightarrow$ from MC**

Monte Carlo Validation Method



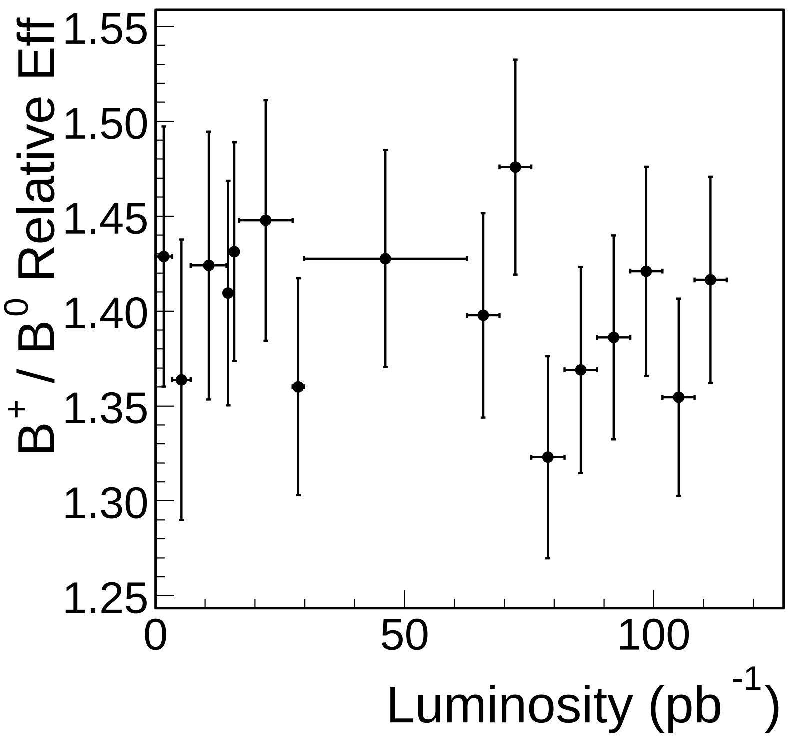
- **high and low-mass sideband: different composition**
- **subtract only high-mass sideband**
- **but scale up number of events (using the exponential fit for the comb. background)**
- **check relevant distributions for both B^0 and B^+**
- **in addition, check N-1 cut efficiencies**

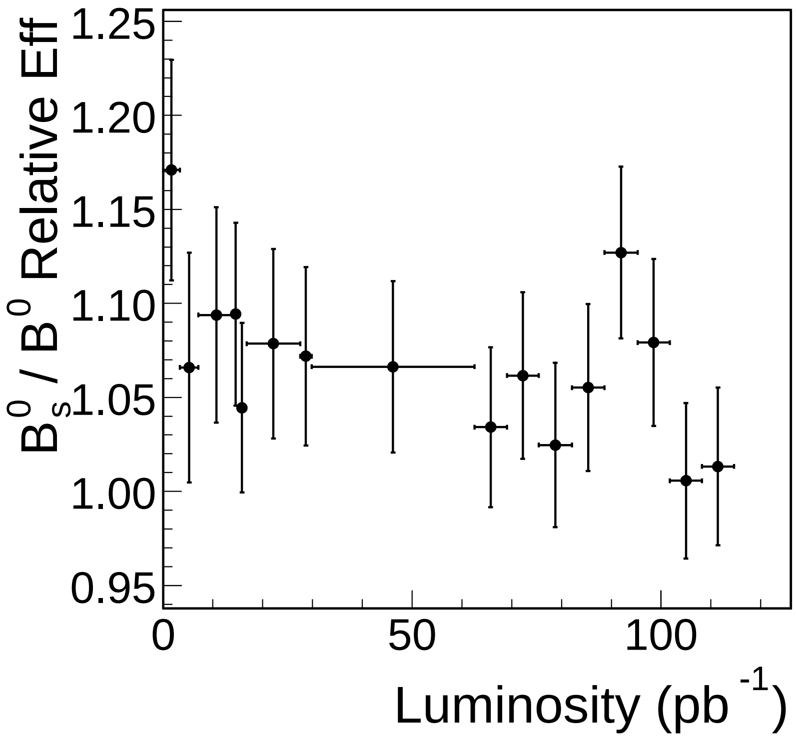
Monte Carlo Validation



- **check many variables, good agreement for most**

Stability of Efficiency Ratios:





- trigger was constantly being upgraded
- concern: this may affect the efficiencies
- the ratio of total efficiencies is stable regardless of trigger efficiency change
- measurement quite robust to trigger conditions

Systematic Uncertainties:

Effect	Syst. Unc.
$B\ p_T$ spectrum	± 1.5 %
XFT simulation	± 0.1 %
ϕ^0 mass cut	± 1.0 %
cut efficiencies	± 5.0 %
B_s^0 lifetime	± 1.4 %
D_s^+ lifetime	± 0.3 %
B^0 lifetime	± 0.4 %
D^+ lifetime	± 0.04%
B_s^0 fitting	± 5.0 %
B^0 fitting	± 7.0 %
Total	± 10.2 %

Measurement Results:

$$\frac{f_s}{f_d} \cdot \frac{Br(B_s^0 \to D_s^- \pi^+)}{Br(B^0 \to D^- \pi^+)} = 0.35 \pm 0.05(stat) \pm 0.04(syst)$$
$$\pm 0.09(BR)$$

Using the world average value for $\frac{f_s}{f_d}$ $\left(\frac{f_s}{f_d} = 0.26 \pm 0.03\right)$ we obtain:

$$\frac{Br(B_s^0 \to D_s^- \pi^+)}{Br(B^0 \to D^- \pi^+)} = 1.4 \pm 0.2(stat) \pm 0.2(syst)$$
$$\pm 0.4(BR) \pm 0.2(PR)$$

Our measurement assumes the same fragmentation model for B_s^0 and B^0 mesons.

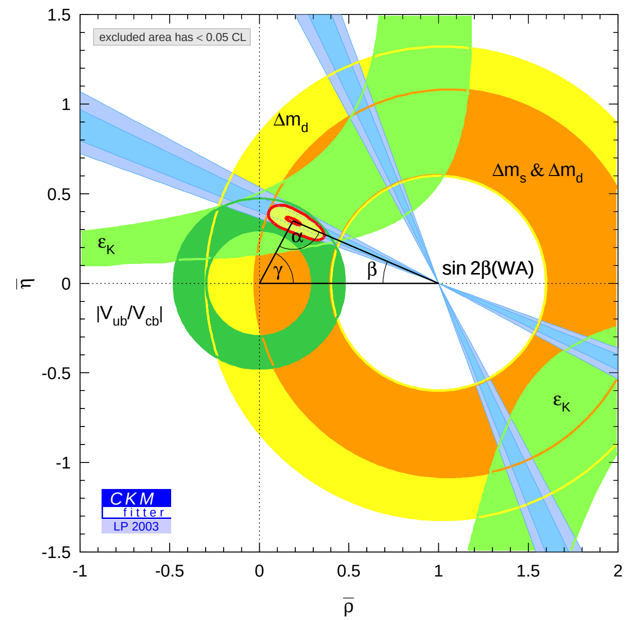
... now we can estimate our B_s mixing reach

B_s^0 Mixing Reach Estimates

- **Current performance:**
- $S = 1600/\mathrm{fb}^{-1}$, $\mathrm{S/B} = 2:1$
- $\epsilon D^2 = 4\%, \sigma(ct) = 67$ fs

- **With "modest" improvements:**
- $S = 2000/\mathrm{fb}^{-1}$, $\mathrm{S/B} = 2:1$
  (improve trigger, more modes)
- $\epsilon D^2 = 4\%, \sigma(ct) = 50$ fs
  (event by event prim vertex, Si on beampipe)
- **3σ sensitivity for $\Delta m_s = 18\ \mathrm{ps}^{-1}$ with 1.3 fb^{-1}**
- **5σ sensitivity for $\Delta m_s = 18\ \mathrm{ps}^{-1}$ with 1.7 fb^{-1}**
- **5σ sensitivity for $\Delta m_s = 24\ \mathrm{ps}^{-1}$ with 3.2 fb^{-1}**
- **this is a difficult measurement**

Conclusions



- B_s mixing at CDF II at a glance:
- initial work has begun
- reconstructed signal mode, understand rate
- work on tagging currently in progress, promising
- not a particle discovery, 3σ is relevant!
- $\longrightarrow$ we want to constrain the unitary triangle
- expect to surpass world limit with 1 year of data
- beyond that, need to work on ct resolution and taggers to further extend reach
- push for more luminosity and gather more data

B Mixing: $p\bar{p}$ vs $\Upsilon(4S)$

Quantity	$\Upsilon(4S)$	$p\bar{p}$
Mixing B Mesons	B^0	B^0, B_s^0
$\sigma(B)$	~ 1 nb	$\sim 100\ \mu$b
$\sigma(B)/\sigma(other)$	$\sim 1:5$	$\sim 1:1000$
ct resolution	~ 1.1 ps	~ 70 fs
tag. power (ϵD^2)	$\sim 30\%$	$\sim 5\%$

- higher B production cross section, produce B_s
- immersed in light quark background
- triggering much more important
- B's boosted in the transverse plane
- less production flavor information